

Title page

Article Title: NO_x reduction in waste incinerators by SCR instead of SNCR compared from a life cycle perspective: a case study

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Highlights

- SCR has a has a higher NOx removal efficiency than SNCR
- Switching from SNCR to SCR reduces the direct environmental impact of a typical hazardous waste incinerator
- The indirect environmental impacts of SCR are higher than those of SNCR
- Switching from SNCR to SCR increases the net environmental impact of the incinerator, particularly in the impact category global warming
- From an environmental point of view optimizing existing SNCR should be preferred

Abstract

In most modern waste incinerators selective non catalytic reduction (SNCR) is applied to remove NO_x from the combustion gas to reach the European emission limit value (ELV) of 200 mg/Nm³. If however the NO_x-ELV for waste incinerators would be lowered to e.g. 100 mg /Nm³, SNCR, with a typical NO_x removal efficiency of around 50%, would not suffice to reach the new ELV. In that case, selective catalytic reduction (SCR), with a NO_x removal efficiency of up to 90% in tail-end configuration could be an interesting alternative. However, from a life cycle perspective, the production, construction and operation of SCR equipment including the catalyst, also involve indirect (i.e. not from the process itself but related to other parts of the life-cycle) pollutant emissions and resource consumption with resulting environmental impacts. By means of a case study of a typical hazardous waste incinerator it is illustrated that replacing SNCR by tail-end SCR reduces the direct environmental impact of the incinerator (i.e. environmental impact of the NO_x emitted at the stack) in the impact categories acidification, eutrophication and photo-oxidant formation, as expected from the lower NO_x emissions in case of SCR. However, mainly due to the need to reheat the combustion gas, SCR has higher indirect impacts than SNCR, most notably in the impact category global warming. Because of these indirect impacts, the mentioned direct environmental impact reductions of SCR in the impact categories acidification, eutrophication and photo-oxidant formation are no net environmental benefits; when e.g. fuel oil is used as an energy source to reheat the flue gas, the indirect impact in the impact categories acidification and photo-oxidant formation is higher than the direct impact reduction related to the lower NO_x concentration in the flue gas emitted at the stack of the installation. In this case, there is only a net environmental benefit in the impact category eutrophication. Overall it can be concluded that in the hazardous waste incinerator under study, which is representative in its field, replacing SNCR by SCR to reach a new, lower ELV, increases the net overall environmental impact of the incinerator, particularly in the impact category global warming. From an environmental point of view optimizing existing SNCR should be preferred over installing tail-end SCR for existing installations such as the considered hazardous waste incinerator.

Keywords

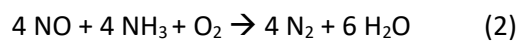
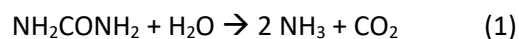
NO_x, SCR, SNCR, LCA, waste incineration

1 Introduction

In waste incinerator flue gas, about 95% of NO_x (sum of NO and NO₂) is present as NO (Gómez-García et al., 2005; Gohlke et al., 2010). NO is a relatively harmless gas, but once released in the atmosphere, it reacts within minutes to hours with oxygen to form NO₂. NO₂ is a brown, irritating, acid gas that in the atmosphere can further react with OH-radicals to give nitric acid. In this way, NO_x contribute to acid rain and eutrophication. NO_x also play an important role in the formation of ozone and photochemical smog.

In industrialized countries, the primary anthropogenic source of NO_x is fuel combustion with traffic and power generation being the most important sectors (European Environment Agency, 2015; US Environmental protection agency, 2010). Also the combustion of waste is a (minor) source of NO_x. To protect human health and the environment from the negative effects of NO_x, Directive 2010/75/EU on industrial emissions (IED) implements emission limit values (ELVs) for NO_x for different types of combustion plants. For waste incineration plants the ELV for NO_x is 200 mg/Nm³. Primary measures such as air or fuel staging usually do not suffice to reach this ELV. Therefore, secondary measures are necessary and selective non catalytic reduction (SNCR) is most often applied, as it is relatively simple and cost-efficient (De Greef et al., 2013). SNCR involves injection of ammonia (NH₃) or of urea (NH₂CONH₂), which readily decomposes into ammonia (reaction 1), in the combustion gas directly

after the post combustion chamber where the gas temperature is typically around 1000 °C. At this temperature, ammonia reacts with NO_x, to give harmless N₂ and H₂O (reaction 2). In waste incinerators, SNCR has typically a NO_x removal efficiency of around 50% and is usually capable of reducing the NO_x concentration in the combustion gas to concentrations below the current ELV (Villani et al., 2012). If however the NO_x-ELV for waste incinerators would be lowered to e.g. 100 mg /Nm³, as is already the case in some regions in Germany (Gohlke et al., 2010), this would require the installation of additional or other techniques to further reduce the NO_x concentration in the combustion gas. One of the options is selective catalytic reduction (SCR), where ammonia reacts with NO to give N₂ on a TiO₂/V₂O₅/WO₃ catalyst surface, at much lower temperatures: typically between 220 and 350 °C (Gómez-García et al., 2005). SCR has a higher NO_x removal efficiency than SNCR of up to 90% in tail-end configuration in municipal solid waste (MSW) incinerators (Goemans et al., 2004).



When one focuses only on direct emissions i.e. emissions from the process as such, a switch from SNCR to SCR seems an obvious choice to meet a more stringent emission limit for NO_x in waste incinerators. It should however be kept in mind that, from a life cycle perspective, the production, construction and operation of SCR equipment including the catalyst, also involve indirect (i.e. not from the process itself but related to other parts of the life cycle) pollutant emissions and resource consumption with resulting environmental impacts. These indirect impacts may not be neglected when selecting a NO_x reduction technique. This paper carries the idea further and illustrates it by a case study of a typical hazardous waste incinerator. The methodology applied for the comparison from a life cycle perspective is similar to that used by Vermeulen et al. (2012) and Billen et al. (2014).

Over the last ten years, many papers on life cycle assessment of waste incineration were published (Fruergaard Astrup et al., 2015). Most of these papers focus on the environmental impact of the waste incinerators as a whole or compare waste incineration to other treatment options. Moberg et al. (2005), for example, compared the environmental impact of recyclable waste incineration with that of landfilling and recycling, whereas Fernández-Nava et al. (2014) compared the environmental impact of MSW incineration with that of anaerobic digestion and landfilling. Only few LCA studies focus on the environmental performance of the flue gas cleaning step in waste incinerators and those who do, mostly focus on the removal of acid gases (Chevalier et al., 2003; Scipioni et al., 2009). The novelty of this paper, which focusses on NO_x removal, lies in the fact that it considers the environmental impact of switching from SNCR to SCR in an actually existing waste incinerator, considering practical limitations. The aim is to evaluate, from a life cycle perspective, whether lowering the NO_x ELV will lead to an overall environmental impact reduction or not.

2 Materials and methods

2.1 Hazardous waste incinerator installation

The hazardous waste incinerator under study, located in Antwerp, Belgium, is of the rotary kiln type and has a capacity of 110,000 t of waste /year. The NO_x concentration in the combustion gas is reduced by SNCR: an aqueous NH₃ solution is directly injected by means of different lances in the

first pass of the boiler, where the temperature of the combustion gas is about 1000°C. After exchanging heat in the boiler, the combustion gas is dedusted in an Electrostatic precipitator (ESP), flows through a four stage wet scrubber for acid gas removal and finally flows through an activated carbon filter for PCDD/F adsorption. A schematic representation of the installation is given in Figure 1. For all regulated pollutants e.g. PCDD/Fs, PM10, heavy metals, SO₂, etc., the concentration in the flue gas emitted at the stack is well below the ELVs provided in the IED. A more detailed description of the installation and its environmental performance is given in Block et al. (2015).

The daily average concentration of NO_x in the emitted combustion gas is about 110 mg/Nm³ i.e. below the actual ELV. If however the NO_x-ELV would be lowered to 100 mg/Nm³, the existing SNCR no longer suffices. SCR has generally a higher NO_x-reduction efficiency and could be an alternative for reaching the lower ELV. Classic TiO₂/V₂O₅/WO₃ catalysts are very sensitive to plugging by dust and salts, and to corrosion by SO₃ (Kling et al, 2007). Therefore, and because of spatial limitations, in most existing waste incinerators including the hazardous waste incinerator under study, they can in practice only be placed downstream of the flue gas cleaning installation, where the temperature of the combustion gas is generally about 100 °C or lower. This implies that the combustion gas has to be reheated for the SCR to be effective.

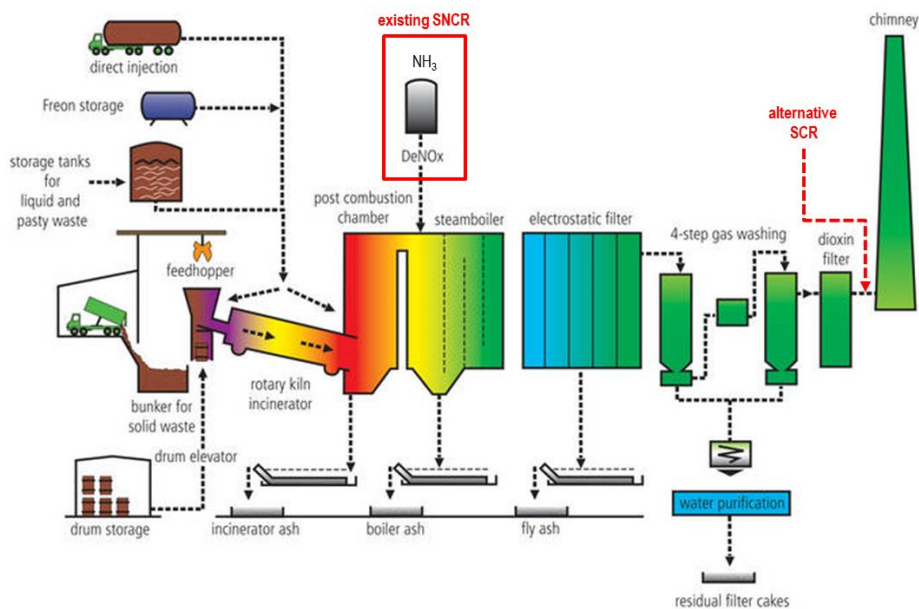


Figure 1. Schematic representation of the hazardous waste incinerator under study

2.2 Goal and scope definition

The goal of this study is to compare quantitatively, from a life cycle perspective, the environmental impacts of NO_x reduction by SCR to the one of NO_x reduction by SNCR in the hazardous waste incinerator described in Section 2.1. The functional unit is the reduction of NO_x in the combustion gas of this hazardous waste incinerator from 220 mg/Nm³ to a level below the ELV, during one year. Two alternatives for NO_x reduction are considered (Figure 2):

- The actual situation: reduction by SNCR with NH₃ injection in the hot combustion gas in the post combustion chamber just before the boiler entry. The actual obtained NO_x reduction efficiency is 50%, so the NO_x concentration in the treated gas is 110 mg/Nm³.
- Tail-end SCR, with a classic TiO₂/V₂O₅/WO₃ catalyst installed directly downstream of the wet scrubbers, before the PCDD/F filter. The NO_x reduction efficiency of this alternative is assumed to be 80%, based on data reported in the literature (Beretta et al., 1998, Goemans et al., 2004; Mahmoudi et al., 2010), corresponding to a NO_x concentration in the treated gas of 44 mg/Nm³. The temperature of the combustion gas at the exit of the wet scrubbers is about 70 °C (100% rel. hum.), so the gas has to be reheated to 230 °C, the temperature at which tail-end SCR installations in waste incineration installations are typically operated (Gohlke et al., 2010). The heat needed to raise the temperature of the gas before it enters the catalyst unit is generated by combustion of natural gas or, alternatively, fuel oil.

The SNCR alternative is chosen as the reference situation.

The results of this study are the differences in environmental impacts between the SCR alternative and the reference situation (SNCR). The differences can be negative, meaning that the environmental impact of NO_x removal with SCR is lower than with SNCR, or can be positive, meaning that the environmental impact of SCR is higher than the impact of SNCR. The following aspects of SCR are taken into account:

- Generation of the heat necessary to reheat the combustion gas before it enters the catalyst unit using natural gas or fuel oil as energy source.
- Production of steel, TiO₂ and other (catalytic) material needed for the production of the catalyst unit.
- Generation and transport of electricity consumed by the fan needed to overcome the pressure drop caused by the catalyst unit.
- Final disposal of the catalytic material on a landfill site for inert waste.

Per cubic meter of emitted combustion gas, SCR removes 66 mg NO_x more than SNCR. The production and transportation of NH₃ needed for this additional NO_x reduction is also considered in the calculations.

The following minor aspects of the SCR alternative are not considered, mainly because no reliable data were available to correctly quantify their environmental impact:

- Extra consumption of steam as carrier for NH₃.
- Maintenance operations e.g. cleaning of the catalyst unit.

The implications of not including these aspects are further discussed in the sensitivity analysis in Section 3.3.

The NH₃-slip at the stack is considered equal for both alternatives. This assumption is based on the literature (Goemans et al., 2004; Beckmann et al., 2009; Villani et al., 2012), where NH₃ concentrations of 0.5 – 5 mg/Nm³ stack gas are reported both for incinerators equipped with SNCR or with SCR.

Aspects that are the same for SCR (alternative 2) and SNCR (alternative1, reference) e.g. NH₃ preparation and injection equipment have obviously not to be taken into account and are therefore also not indicated in Figure 2.

2.3 Emission inventory and impact calculation

Details on relevant emissions and amounts of resources consumed in the SCR alternative are given in Table 1 and in Figure 2.

Table 1. Emission and consumption data (on a yearly basis) used for the calculation of the environmental impacts of SCR compared to SNCR in the hazardous waste incinerator under study

Amount of flue gas to be treated	815,599,000	Nm ³ /year	Indaver, 2011
NO _x additionally removed by SCR	53,830	kg/year	
Energy needed to reheat combustion gas	1.84 10 ⁸	MJ/year	Reheat from 70 °C (100% rel. hum.) to 230 °C
Additional NH ₃ needed	33,554	kg/year	Molar ratio NH ₃ /NO = 1.1
Additional electricity consumption fan	3,187,757	MJ/year	Based on Gohlke et al., 2010
Materials needed for catalyst-unit:			
Steel	3,290	kg/year	Based on Liang et al., 2011
TiO ₂	56	kg/year	Based on Liang et al., 2011
Other catalytic material ^a	19,638	kg/year	Based on Liang et al., 2011
Inert waste to landfill	19,694	kg/year	Catalyst + TiO ₂

^a Liang et al. (2011) do not give details on the composition of the catalyst material. In general catalytic material contains besides TiO₂, WO₃ and V₂O₅ also silica, alumina and calcium oxide (BASF, 2004).

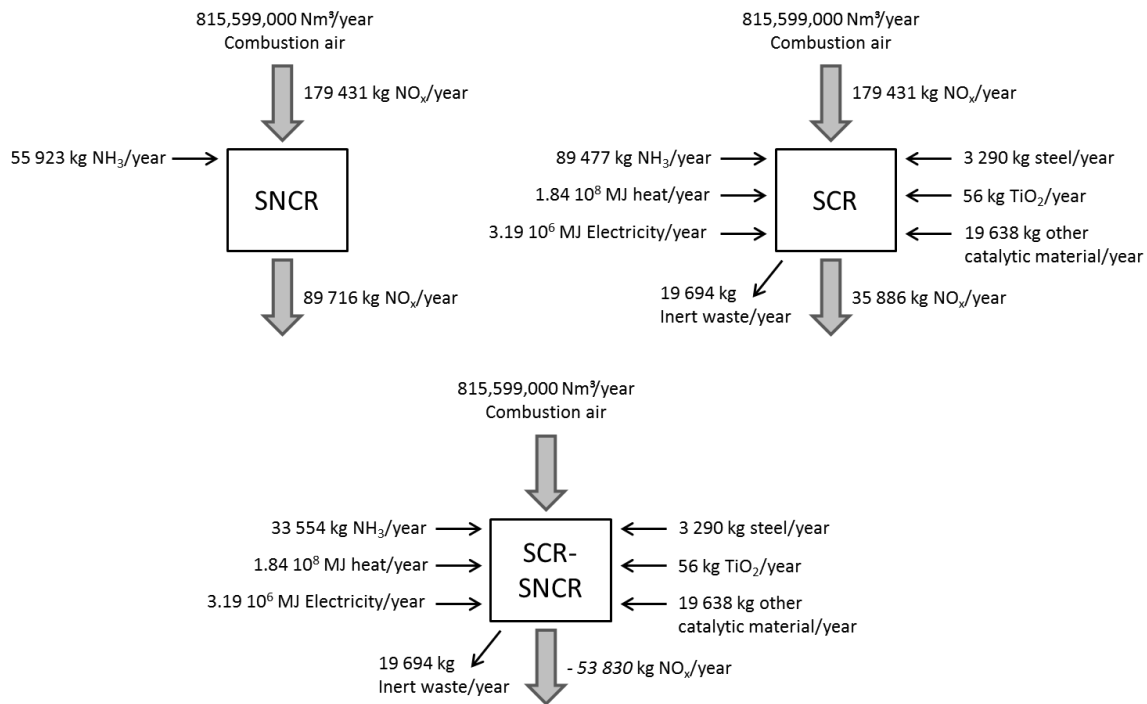


Figure 2. Schematic representation of the considered mass flows in the SCR and SNCR alternative and the difference between these two alternatives

The impacts of the generation of heat (natural gas or fuel oil), NH₃, steel, TiO₂ and electricity and of the disposal of waste catalytic material on an inert waste landfill, were calculated from the eco-invent 2.2 database with SIMAPRO 7 LCA software, using CML 2001 characterization factors. The environmental impacts, expressed per impact category and per unit of energy or mass, are given in Table A1 in appendix A. The eco-invent 2.2 database does not provide an emission inventory for the production of catalytic material (including V₂O₅ and WO₃), only for the production of TiO₂. For catalytic material other than TiO₂, the emission inventory was taken from Liang et al. (2011) and the resulting environmental impacts were calculated in an excel worksheet using CML characterization factors. As the number of pollutants in the emission inventory of Liang et al. (2011) is limited (e.g. emissions of heavy metals are not included, see Table A.2), the environmental impact of the production of catalyst material is underestimated compared to the environmental impacts associated with the consumption of the other resources based on the eco-invent 2.2 database.

2.4 Normalization

The calculated impacts were normalized by dividing them by the impacts of the yearly (2010) total pollutant emissions of Flanders (the region where the incinerator is located). Normalization data are given in Table A.3. For the impact categories acidification, eutrophication, human toxicity and photochemical oxidation, these impacts were calculated by multiplying the yearly pollutant emissions for Flanders for the year 2010, reported by the Flemish Environmental Agency (Vlaamse Milieumaatschappij, 2013), by the CML characterization factors and summing the obtained products relevant per impact category. For the impact categories global warming and ozone layer depletion the impacts are directly provided by the Flemish Environmental Agency (Vlaamse Milieumaatschappij, 2012). For the impact categories abiotic depletion and freshwater aquatic ecotoxicity no normalization factor could be established as no comprehensive consumption and emission data are available for the Flemish regional level.

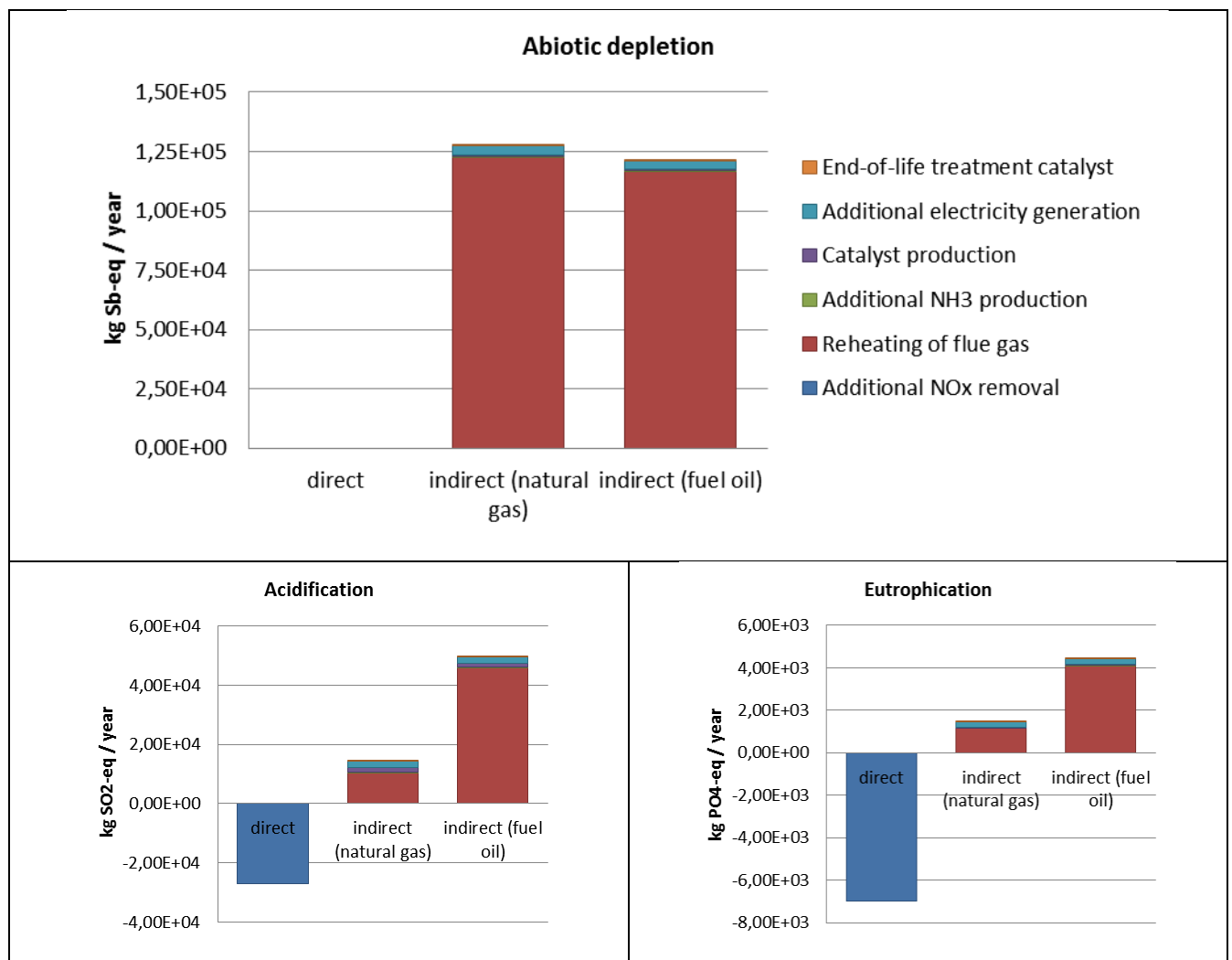
Normalization factors for Flanders were preferred to continental or global normalization factors because they can be derived from recent, comprehensive and readily available data reported by the local government's Environmental Agency. Furthermore they were considered the most relevant since the waste incinerator under study is located in Flanders. However, in Section 3.3.2, the reported environmental impacts will, as a kind of sensitivity analysis, also be normalized by means of the factors for Western Europe for 1995 as advised by the CML methodologists (CML-IA database, 2013).

3 Results and discussion

3.1 Results per impact category

This section gives and discusses the *differences* in environmental impact of the SCR alternative and the reference situation (SNCR), based on the mass and energy flows given in Figure 2.

As discussed in Section 2.2, the NO_x concentration in the gas emitted at the stack is 60 % lower with SCR than with SNCR. SCR will decrease the direct environmental impact (in this case the impact of NO_x emitted at the stack) of the considered hazardous waste incinerator in the impact categories acidification, eutrophication, photochemical oxidation and human toxicity, as graphically represented by the left, (blue) bars denominated "direct" in Figure 3.



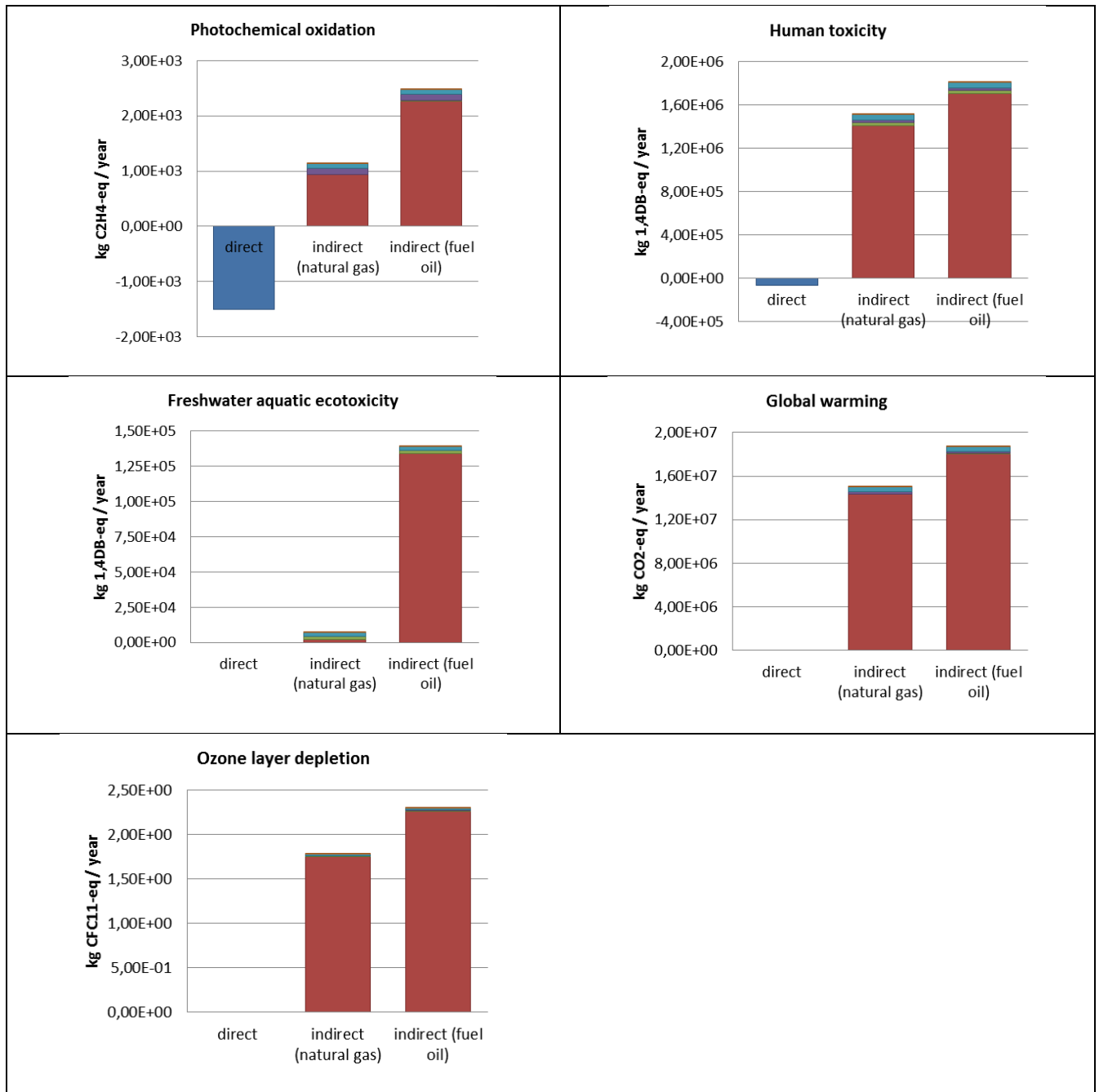


Figure 3. Difference of the yearly direct and indirect environmental impacts between SCR and SNCR in the hazardous waste incinerator under study

The graphs in Figure 3 also show that the reduction of the direct impacts due to reduction of NO_x emissions at the stack with SCR are no net gains. Indeed, the production of the catalyst needed for the reduction and the additional consumption of electricity and NH_3 and of heat have, from a life cycle perspective, also an impact in the considered impact categories. These impacts are represented by different colors in the bars denominated “indirect” in Figure 3. The highest such impacts in all considered impact categories come from the generation of heat (by combustion of natural gas or fuel oil) needed to reheat the flue gas before it enters the catalyst unit. This necessary reheating of the flue gas accounts for 74 to 99% of the total difference in indirect impacts between SCR and SNCR, except for the impact category freshwater aquatic ecotoxicity in case natural gas is used as energy source where the contribution of the reheating is limited to 24%. The second most important source of the indirect impact is the generation of the electricity consumed by the extra fan needed to

overcome the pressure drop in the catalyst unit of the SCR, which accounts for a few percent of the total indirect impact in the impact categories abiotic depletion, global warming, ozone layer depletion, human toxicity and photochemical oxidation, for about 15% in the impact categories acidification and eutrophication (heating with natural gas) and to 41% in the impact category freshwater aquatic ecotoxicity (heating with natural gas). The contribution of the catalyst production is only significant in the impact category acidification in case natural gas is used as energy source for the reheating of the flue gas (10% of total indirect impact). The environmental impacts of the production of the extra NH_3 and the landfilling of the waste catalytic material are insignificant compared to the impacts of the other indirect sources. As discussed in Section 2.2, the environmental impacts of the production of the steam needed as carrier for the extra amount of NH_3 that has to be injected and of the maintenance of the catalyst in the SCR alternative were not taken into account in the calculations. It is however clear that these environmental impacts would be of little significance compared to the predominant indirect impacts of the reheating of the flue gas, given the small amounts of materials and energy involved in these two processes.

Figure 3 also shows that in all impact categories except abiotic depletion, the environmental impact of reheating the flue gas with fuel oil as an energy source is higher than for reheating the flue gas with natural gas. In the impact category acidification this is due to the higher NO_x and SO_x emissions of fuel oil combustion. The higher impact in the impact category eutrophication it also predominantly due to the higher NO_x emissions. In the impact category human toxicity and ecotoxicity the higher impact of the fuel oil alternative is caused by higher heavy metal emissions. The difference in CO_2 emissions, (impact category global warming) can obviously be explained by the difference in chemical composition between natural gas and fuel oil: natural gas has a higher H/C ratio. The higher impact of the fuel oil alternative in the impact category photochemical oxidation is due to higher SO_x and VOC emissions during combustion and transportation of fuel oil. Finally, the higher impact in the impact category ozone layer depletion is caused by slightly higher CFC emissions in the upstream (production) process of fuel oil.

In the case of reheating with natural gas, the indirect impacts (bars in the middle in Figure 3) partially neutralize the direct impact reduction (left, negative bars in Figure 3) obtained in the impact categories acidification, eutrophication and photochemical oxidation. In the case of reheating with fuel oil (bars on the right in Figure 3), the indirect environmental impact in the impact categories acidification and photochemical oxidation exceed the impact directly avoided by the lower NO_x emission at the stack of the hazardous waste incinerator. So in this case switching from SNCR to SCR would increase the overall environmental impact of the incinerator in these impact categories. In the impact category human toxicity, the indirect impact of SCR is more than twenty times higher than the impact directly avoided by the lower NO_x emission. So, also in this impact category there is no gain by installing SCR instead of SNCR, on the contrary, because of the indirect emissions this alternative has a higher overall environmental impact. The indirect emissions of SCR also result in, compared to SNCR, additional impact in the impact categories global warming, ozone layer depletion and abiotic depletion.

3.2 Normalized impacts

Figure 4 gives the overall difference in environmental impacts i.e. the sum of the direct and indirect environmental impacts given in Figure 3, normalized by dividing them by the impacts of the yearly (2010) total pollutant emissions of Flanders (the region where the incinerator is located).

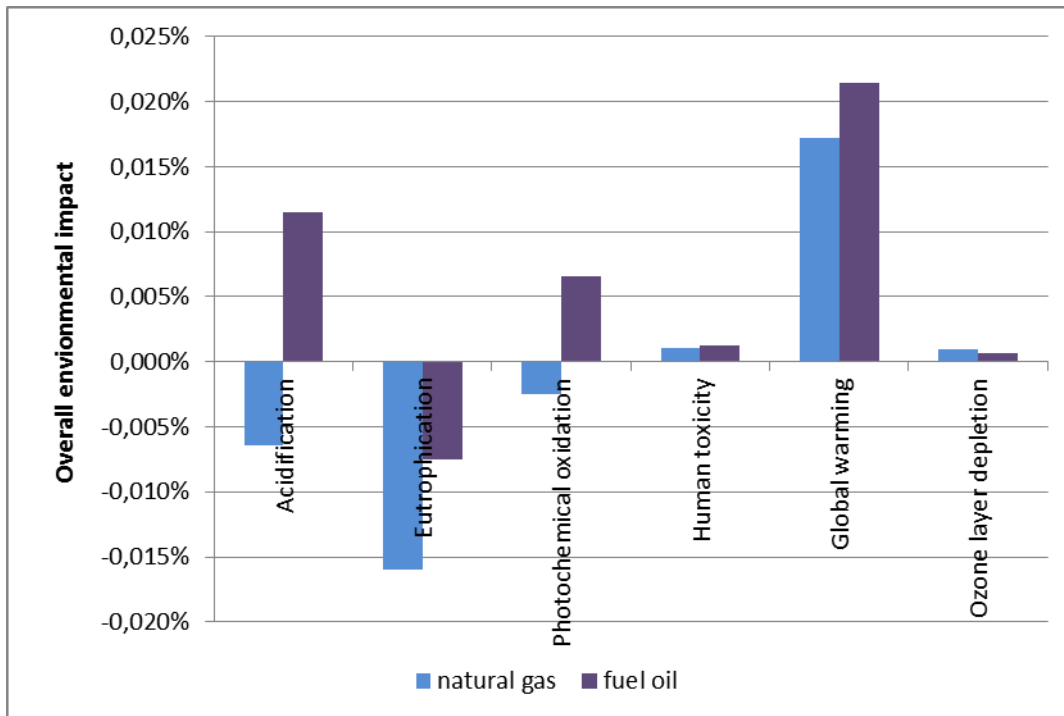


Figure 4. Normalized overall difference in environmental impacts between SCR and SNCR in the hazardous waste incinerator under study

Figure 4 shows that in this particular case a switch from SNCR to SCR with reheating of the combustion gas by combustion of natural gas will decrease the impact in the impact categories eutrophication, acidification and photochemical oxidation, where a reduction of 0.016%, 0.006% and 0.003% of the total yearly Flemish environmental impact is obtained, respectively. The total yearly Flemish impact in the impact category global warming will however increase by 0.017%, primarily because of the combustion of natural gas for the necessary reheating of the incinerator's flue gas. The increase of the impact in the impact categories human toxicity and ozone layer depletion is relatively limited (both 0.001% of the total Flemish environmental impact).

If in the SCR alternative fuel oil is used as energy source to reheat the combustion gas of the considered hazardous waste incinerator, there is only a net environmental gain in the impact category eutrophication, corresponding to 0.007% of the total yearly Flemish environmental impact. The total yearly Flemish impact in the impact categories global warming, acidification and photochemical oxidation will however increase by 0.021%, 0.011% and 0.007 % of the total yearly Flemish environmental impact, respectively. The increase of the impacts in the impact categories ozone layer depletion and human toxicity remains relatively low (both 0.001% of the total Flemish environmental impact).

Figures 3 and 4 clearly show that, from a life-cycle perspective, implementing SCR instead of SNCR as NO_x reduction technique reduces impacts in certain impact categories but increases environmental impacts in other impact categories.

The discussed results apply for the hazardous waste incinerator under study, but because the necessary reheating of the combustion gas is the main cause of the additional impact, the results are also applicable to incinerators of other wastes such as MSW with wet flue gas cleaning systems. Indeed, it is the flue gas cleaning system that mainly determines the temperature of the combustion gas at the inlet of the tail-end SCR catalyst and hence determines the amount of energy needed to reheat this gas to the working temperature of the catalyst i.e. 230 °C. The influence of the

temperature of the combustion gas at the end of the flue gas cleaning step on the indirect impacts of the SCR alternative are further discussed in section 3.3.1.

3.3 Sensitivity analysis

3.3.1 High dust SCR

From Section 3.2 it can be concluded that the necessary reheating of the combustion gas is by far the main cause of the additional environmental impact of SCR compared to SNCR for NO_x reduction in an existing incinerator as the hazardous waste incinerator under study. As explained in Sections 2.1 and 2.2 reheating of the flue gas is necessary because classic NO_x reduction catalysts are very sensitive to plugging by dust and also oxidize SO₂ to SO₃, which may react with NH₃ and H₂O to ammonium salts that deposit on the catalyst surface. To overcome these problems, catalyst producers developed “high dust” catalysts for NO_x removal that can be placed more upstream in the installation. These high dust catalysts are generally of the plate type, with wider channels to prevent blocking by dust deposits. Furthermore, the concentration of the active component V₂O₅ is lower (to prevent SO₂ oxidation): typically below 1 w% compared to 6 w% in classic catalysts. Often high dust catalysts also contain relatively more WO₃, thus increasing the resistance to acid attack. Because of the wider channels and the lower V₂O₅ content, the specific NO_x reduction capacity is lower for high dust than for classic, low dust catalysts. As a result, higher catalyst volumes are needed to obtain the same NO_x reduction efficiency than classic, low dust catalysts (Pritchard et al., 2005).

Because the necessary reheating of the combustion gas is the main cause of the additional environmental impact of SCR (Section 3.2), a third alternative i.e. SCR with a high dust catalyst placed after the boiler and thus avoiding the need to reheat the combustion gas, is studied. It is important to note that this “high dust” alternative is purely hypothetical for the waste incinerator under study because there is no space in the installation to put the catalyst unit after the boiler. It can however be an interesting alternative for new installations. To calculate the environmental impact of this third alternative, a NO_x reduction efficiency of 60% is assumed based on practical experience in the hazardous waste incinerator of thermische Rückstandsverwertung (TRV) in Wesseling (Franz-Gunther Zeigner, personal communication), Germany, corresponding to a NO_x concentration in the treated flue gas of 88 mg/Nm³ which is still below the supposed new emission limit of 100 mg/Nm³. It is also assumed that the environmental impacts of the production of the catalyst and of the electricity consumed by the fan to overcome the extra pressure drop are equal to the impacts in the SCR alternative. The amount of NH₃ necessary to reduce the NO_x concentration by 60% equals 11,185 kg/year.

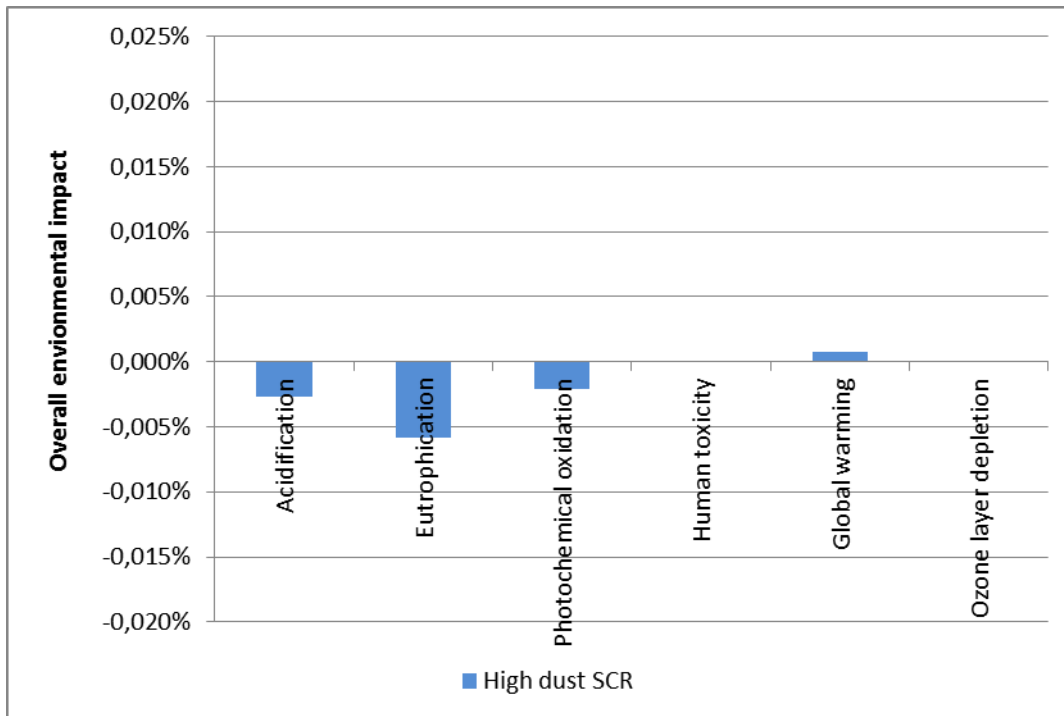


Figure 5. Normalized overall difference in environmental impacts between SCR “high dust” and SNCR in the hazardous waste incinerator under study

Figure 5 gives the normalized differences in overall environmental impacts between SCR “high dust” and SNCR. Comparing Figures 4 and 5 shows that the reduction of the environmental impacts in the impact categories acidification, eutrophication and photochemical oxidation is about half of the impact reduction in the classic SCR alternative. However, because in the high dust alternative the combustion gas does not have to be reheated, there is only a limited increase of impact in the impact category global warming, which is mainly caused by the production of the NH_3 and the catalyst. Figure 5 shows that high dust catalyst could be an interesting alternative for SNCR in new installations or in installations where space is available to place the catalyst after the boiler. It should however be noted that a reduction efficiency of 60% can also be obtained by optimizing SNCR, which is often economically more favorable and does not require maintenance and regular replacement of the catalyst (Villani et al., 2012). This however only holds if the increase of reduction efficiency is obtained by optimizing the injection and mixing of NH_3 in the combustion gas and not by only increasing the NH_3 dosage. In the latter case, the NH_3 slip, which is the emission of unreacted NH_3 , increases, causing an environmental impact that can, in the worst case, be higher than the impact avoided by the higher NO_x removal (Moller et al., 2011).

In waste incinerator installations equipped with a dry or semi-dry system for acid gas removal e.g. in MSW fired Waste-to-Energy (WtE) plants, a classic denox catalyst could be placed at the exit of the bagfilter. However, at this stage the temperature of the combustion gas is typically around $140\text{ }^\circ\text{C}$ so reheating is still necessary to obtain a gas temperature of $230\text{ }^\circ\text{C}$ in the catalyst, although the energy consumption will be lower than in the hazardous waste incinerator under study. The only option to avoid reheating and the related environmental impact is to use sodium bicarbonate in a dry acid gas removal system because this neutralizing agent is still reactive at a temperatures of $230\text{ }^\circ\text{C}$. In this case a higher reduction of the environmental impacts can be realized than with SNCR or high dust SCR, with only limited indirect impacts. However, in real scale installations also energetic and economic aspects have to be taken into account: maintaining a combustion gas temperature of $230\text{ }^\circ\text{C}$ in the flue gas cleaning unit might limit the energy recovery in the boiler and reduce the energetic

and related environmental performance of the installation. Also this overall perspective should be taken into account in the choice of the NO_x reduction system.

3.3.2 Normalization data

To normalize the differences in environmental impacts, they were divided by the total environmental impact of Flanders, the region in which the incinerator under study is located. To evaluate the effect of this choice, Figure 6 gives the differences in environmental impacts between the SCR and the SNCR alternatives, divided by the normalization factors for Western Europe (1995) as advised by the CML methodologists (CML-IA database, 2013).

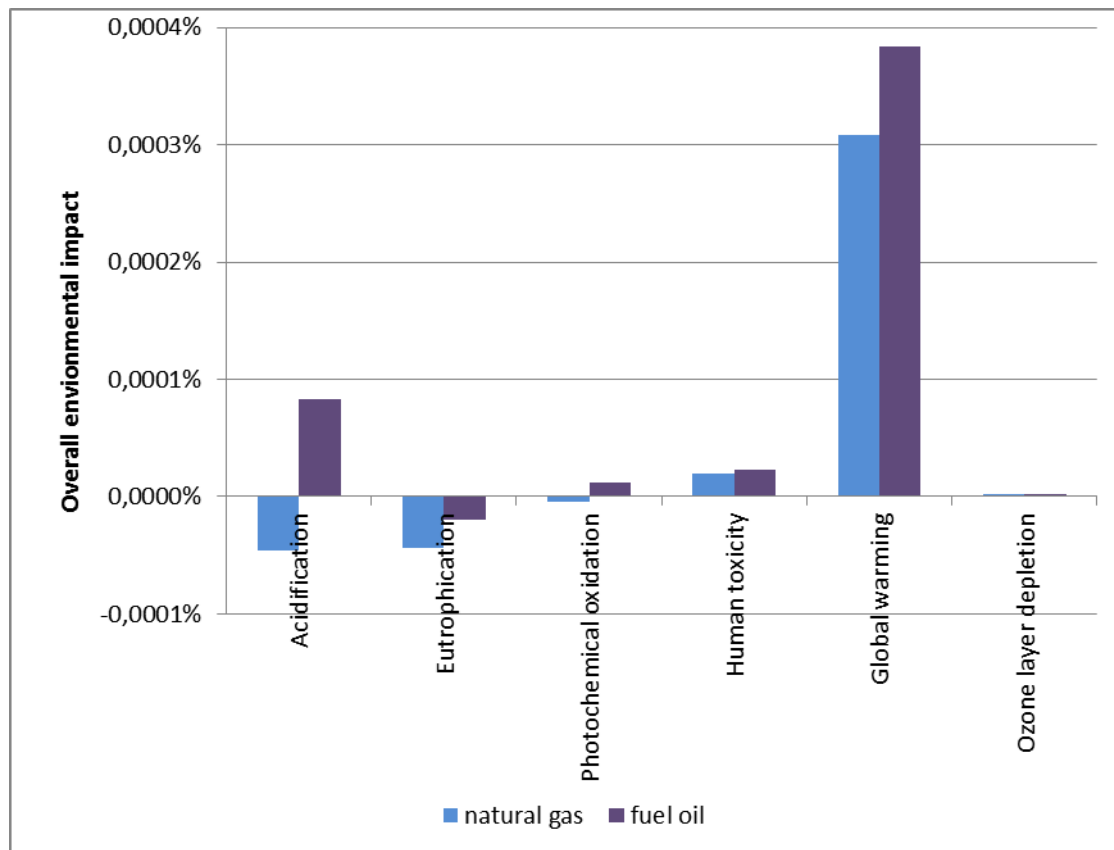


Fig. 6. Normalized overall difference in environmental impacts between SCR and SNCR in the hazardous waste incinerator under study using normalization factors for Western Europe (1995).

Figure 6 and Figure 4 overall show the same image (although the absolute values are of course different): with SCR the environmental impact of the hazardous waste incinerator under study can be reduced in the impact categories acidification and/or eutrophication and photochemical oxidation, depending on the energy source used for the reheating of the flue gas, at the expense of an increase in environmental impact in the impact categories human toxicity, ozone layer depletion and most notably in the impact category global warming. The impact of SCR in the impact category global warming is relatively more pronounced than if the normalization factors for Flanders are used. This can be explained by the high density of energy intensive industry in Flanders which causes high CO₂ emission relative to the emissions of other pollutants. Furthermore the difference might be explained by fact that the normalization factors for Flanders are based on more recent emission data i.e. for 2010 instead of 1995 for the normalization factors of Western Europe: over the past 20 years the emission (per unit of energy generated) of typical combustion related pollutants such as SO₂ and

NO_x has decreased due to specific measures e.g. pre or post desulphurization, whereas a reduction of CO₂ emission per unit of energy generated is limited by the fuel composition.

4 Conclusions

If the NO_x-ELV for waste incinerators would need to be lowered to e.g. 100 mg /Nm³, switching from SNCR to SCR, which has a higher reduction efficiency, might seem an obvious choice. However, the production, construction and operation of an SCR installation including the catalyst, also involve indirect pollutant emissions and resource consumption with resulting environmental impacts. A case study of a typical hazardous waste incinerator showed, from a life cycle perspective, that replacing SNCR by tail-end SCR reduces the direct environmental impact of the incinerator (i.e. environmental impact of the NO_x emitted at the stack) in the impact categories acidification, eutrophication and photo-oxidant formation, as expected from the lower NO_x emissions in case of SCR. SCR however involves higher indirect impacts (i.e. impacts related to the production and operation of the catalyst unit) than SNCR in all impact categories, mainly due to the need to reheat the combustion gas. When fuel oil is used as an energy source to reheat the flue gas, these indirect impacts are higher than the impacts directly avoided by the lower NO_x emissions at the stack in the impact categories acidification and photochemical oxidation, so there is only a net environmental gain in the impact category eutrophication. When natural gas is used as an energy source to reheat the flue gas there is a net environmental gain in all three impact categories (acidification, eutrophication and photo-oxidant formation). For the hazardous waste incinerator under study, which is representative in its field, replacing SNCR by SCR increases the overall environmental impact of the incinerator, particularly in the impact category global warming. Such a shift of impacts from one impact category (in this particular case: eutrophication) to another (global warming) is in contradiction with the IPPC idea. In the field research has shown that small technical adaptations to existing SNCR systems can significantly decrease NO_x emission with only a minor increase of indirect environmental impacts (De Greef et al., 2013). For existing installations such as the hazardous waste incinerator under study, optimizing existing SNCR should, from an environmental point of view, be preferred over installing tail-end SCR.

For new installations where space is available to place the catalyst after the boiler, avoiding the need to reheat the combustion gas and its related environmental impacts, high dust SCR could be an alternative for SNCR. However, because of the lower specific NO_x reduction capacity of high dust catalysts, higher catalyst volumes are needed to reach the same reduction efficiency as the classic catalysts, significantly increasing the cost of the installation.

In waste incinerators equipped with a dry or semi-dry flue gas cleaning system as is often the case in MSW fired WtE plants, a classic denox catalyst placed at the exit of the bagfilter could be an alternative if the NO_x ELV cannot be reached with SNCR. However, in that case, for the catalyst to be active, a gas temperature of at least 230 °C needs to be maintained, which might limit the energy recovery in the boiler and reduce the energetic and related overall environmental performance of the installation.

Acknowledgements

The authors kindly acknowledge Dr. Kenneth Villani for his useful comments and information. Also the members of Eurits are acknowledged for reviewing the data and for providing practical information.

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